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Design and characterisation of low-cost thick-film piezoresistive force sensors for the 100 mN to 100 N range

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Abstract: Two simple low-cost thick-film force sensor designs are optimised, characterised and tested in this work, combining calculations of sensor element and joint stresses, joint strength characterisation and measurement of complete sensors. All sensors are based on standard hybrid substrates. Our results show that a single sensor geometry cannot cover such a wide range of forces in an optimal way. For small forces (100 mN to ca. 2 N), simple cantilever force sensors are an excellent solution, achieving reasonable precision with a very simple design and compatibility with an SMD (surface mount device) assembly process with solder or conductive glue. Characterisation of solder joint strength shows that such joints can reliably withstand the bending moments resulting form the loading of the cantilever sensor up to ca. 2 N. Above this force, both solder joint and cantilever strength become critical in the cantilever design. Therefore, a 3-point or 4-point bending beam geometry must be selected, thereby extending the force range to ca. 100 N.

Key words: thick-film force sensors, cantilever beams, bridges.

1. INTRODUCTION

1.1. General introduction

Thick-film piezoresistive pressure and force sensors have found wide application [1], due to their advantageous combination of good performance, ruggedness and suitability for mass production. Some examples of different force and pressure sensor bodies are given in Fig. 1.

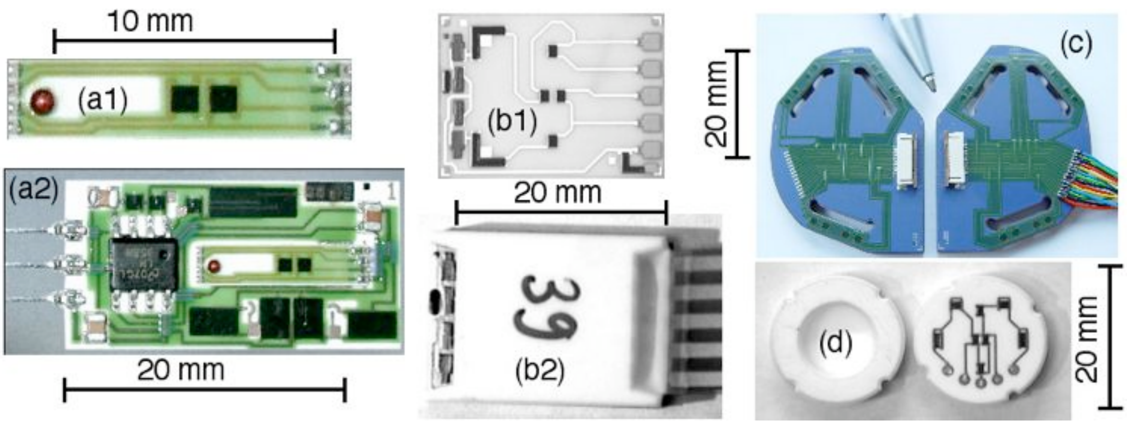

Figure 1. Substrates / bodies for force and pressure sensors. (a1) force sensor, alumina cantilever, for soldering onto base (a2) [2]; (b1) pressure sensor, alumina membrane for glass sealing onto base (b2); (c) force sensor for knee operations [3], sensing bridges machined into steel substrate; (d) pressure sensor, pressed alumina body with integrated membrane.

The main substrate material used for these sensors is 96% alumina, the standard material for thick-film electronics, in spite of its rather mediocre mechanical properties, because of its low cost, guaranteed compatibility with thick-film compositions and wide availability, both in the form of planar substrates of a very wide thickness range and in the form of pressed bodies with integrated sensing shapes such as membranes. The present work deals with simple and low cost force sensors based on planar substrates, which can be produced using classical thick-film techniques without having to resort to specific pressed or machined bodies.

1.2. Substrate materials

Besides alumina, other substrate materials are interesting for various reasons: metals (especially stainless steels), zirconia, zirconia-toughened alumina (ZTA), LTCC and even printed circuit board (PCB) substrates such as FR4. These are discussed below.

- **Metals / stainless steels**. While tremendous improvements over alumina have been demonstrated [4], mass usage of metal-based thick-film piezoresistive sensors will require the development of lower firing thick-film systems [5] due to compatibility issues. Even then, necessity of depositing a relatively thick insulating dielectric will rather restrict the application range to high force or pressure ranges.
- **Zirconia and ZTA**. Zirconia and ZTA have much higher short- and long-term strength than alumina. However, their strength advantage is often decreased, due to long-term degradation of the strength by the thick-film sensing bridge [6].
- **LTCC**. The lower strength of LTCC vs. alumina is more than compensated for by the lower elastic modulus, and further improvements can be gained through the excellent 3D structuring capabilities of LTCC. This is the object of a companion paper in this conference [7].
- **PCB / FR4.** Polymer substrates such as FR4 (epoxy-fiberglass laminate) are a class apart, as they require polymer thick-film compositions, which can also use epoxy resins as a matrix, combined with silver and graphite fillers for conducting and resistive compositions. Compared to other substrates, they potentially allow the highest strains, as they have strength comparable to that of alumina at a far lower elastic modulus. Low cost sensors based on these materials have been demonstrated [8]. However, even relatively stable polymers such as epoxies (our example) have limited thermal stability and are susceptible to moisture effects.

1.3. Force sensor geometries and materials systems studied in the present work

Two force sensor geometries are studied in this work: (1) cantilevers assembled by soldering or gluing, and (2) simply supported bridges (Fig. 2). Cantilevers force sensors are well established [2], but we will show that cantilevers are practically useful only up to a given force range, and that a bridge geometry becomes more advantageous at higher loads. We use here different technologies for both shapes: the standard thick-film technology on alumina for cantilever sensors, and polymer thick-film technology on both alumina and FR4 PCB material for bridge sensors.

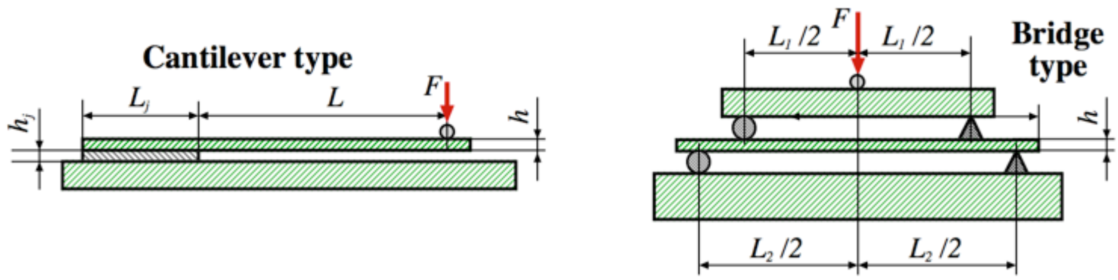

Figure 2. Sensor geometries studied in this work: cantilever beam sensor, clamped at one end & loaded at the other; bridge sensor, loaded in four-point bending (three-point if L_1=0).

2. SIMPLE CANTILEVER SENSORS: PRACTICAL FORCE RANGE

2.1. Beam stresses and deflection

The well-known relations between nominal stress σ_N, displacement y and force F for an ideally clamped cantilever of constant rectangular cross section are given by:

$$\sigma_N = \frac{6 \cdot L}{b \cdot h^2} \cdot F,\ y = \frac{4 \cdot L^3}{E^* \cdot b \cdot h^3} \cdot F \text{ and } E^* = \frac{E}{1-\nu^2} \qquad (1)$$

where: L, b and h are the cantilever free length (between clamping and load point), width and thickness respectively, E^* the effective (plane strain) elastic modulus for $b >> h$, E the material elastic modulus and ν the Poisson coefficient.

For a range of thick-film force sensors where only the thickness of the substrate h used for making cantilevers is varied (the most convenient solution), the expression for deflection can be rewritten:

$$y = \frac{4 \cdot L^3}{E^* \cdot b \cdot h^3} \cdot F = \frac{\sqrt{2 \cdot b \cdot L^3}}{3\sqrt{3}} \cdot \frac{\sqrt{\sigma_N^3}}{E^* \cdot \sqrt{F}} \qquad (2)$$

The displacement therefore increases with decreasing force. Table 1 gives the results for small force sensors. The 0.4…2 N values are for established MilliNewton force sensors [2], and the lower ranges are hypothetical, based on experimentally available thinner alumina substrates. The deflection is given taking into account non-ideal clamping by the joint (see section 2.2), which becomes significant at higher force ranges.

F	Force range	0.1	0.2	0.4	1	2	4	10	N
b	Beam & joint width	3.0	3.0	3.0	3.0	3.0	6	6	mm
E^*	Beam effective elastic modulus	330	330	330	330	330	330	330	GPa
h	Beam thickness	0.13	0.17	0.25	0.40	0.63	0.80	1.27	mm
L	Beam stressed length	8.0	8.0	8.0	8.0	8.0	12.0	12.0	mm
b	Beam & joint width	3.0	3.0	3.0	3.0	3.0	6	6	mm
E_j	Joint effective elastic modulus	30	30	30	30	30	30	30	GPa
h_j	Joint thickness	0.1	0.1	0.1	0.1	0.1	0.1	0.1	mm
σ_N	Calculated nominal beam stress (1)	95	111	102	100	81	75	74	MPa
σ_{j0}	Calculated stress at end of joint	-19	-26	-29	-37	-38	-39	-50	MPa
σ_{jmax}	Calculated max. tensile joint stress	3.9	5.2	5.9	7.2	7.3	7.7	9.6	µm
y	Calculated deflection at full load	100	91	59	37	20	32	21	µm

Table 1. Calculated properties for MilliNewton force sensors (400…2'000 mN), low-range (0.1 and 0.2 N) and high-range extensions (4 and 10 N).

At 100 mN, the nominal displacement starts to become quite large. Using more elastic substrates (increased strength and/or lower elastic modulus) only reinforces this trend. While some deflection is good because it easily allows implementation of stops for overload protection, many force sensor applications require a rather stiff sensor. Moreover, linearity is degraded when the deflection becomes larger than the thickness. One solution would lie in further decreasing the sensor dimensions (length and width), but this is limited by issues with resolution, handling and assembly. Another limitation at small forces is the problematic handling of very thin substrates, with the associated high risk of breakage. A more feasible route would then be to use structured LTCC substrates [7].

At high forces, one must further increase the thickness, which requires a larger cantilever because narrow and thick beams are difficult to individualise. Moreover, we must maintain a minimal length to width ratio of ca. 2. Calculations for reasonable parameters are given for 4 and 10 N in Table 1. On the basis of beam stress alone, we find that we can go to a maximum force of ca. 10 N. However, we will see that the joint stress actually limits the force range to a lower value.

2.2. Stresses in cantilever sensor joints – upper limitation of the force range

Stresses in cantilever sensor joints were evaluated both analytically (purely elastic joint material and “long” joint), and through a more flexible finite difference method. The results of the corresponding calculations, which will be the object of a forthcoming paper, are given in Table 1 and Fig. 3 for the same cantilevers as in section 2.1, assuming a purely elastic solder joint with $E_j = 30$ GPa elastic modulus, $h_j = 100$ µm thickness and $L_j = 5.0$ mm length (essentially equivalent to infinite length). One can note two worrisome results.

- The compressive stress at the end of the joint is very high for a solder. In practice, this means that there will be some local plastic deformation at the end of the joint, especially for higher loads, which can potentially lead to signal drift and to cyclic fatigue problems.
- The maximum tensile stress, which occurs inside the joint, while not a concern for immediate failure, is rather high for long term loading at high temperature, raising the issue of potential creep failure.

Both stresses increase in magnitude with increased force range. The smaller increase for the 2 N sensor is due to the lower nominal cantilever stress, ca. 80 MPa compared to ca. 100 MPa for the two other force ranges. We can see that increasing the force range for these sensors much beyond 2 N is not practical with the current technology. While our calculations suggest that switching to a more compliant joint (glue) would allow some increase in range, going to much higher forces requires a radical change in geometry.

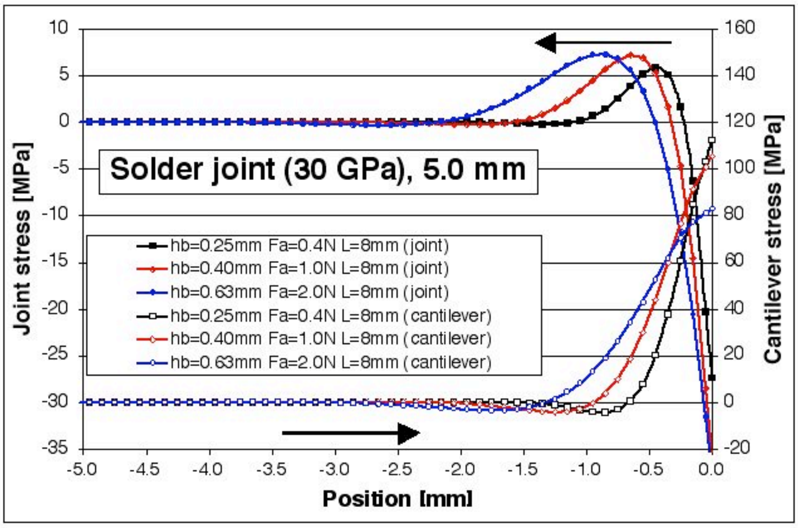

Figure 3. Stresses distribution in cantilever & joint, calculated for 5 mm long purely elastic solder joints.

3. BRIDGE SENSORS

3.1. Design considerations

We take here the case of a bridge (Fig. 2) with simply supported ends, e.g. without clamping of the beam. For this case, the bridge can basically be treated as two cantilevers, separated by a zone with constant bending moment. The corresponding relation between nominal stress σ_N (which is present in the zone between the two loading points) and applied force F is given below.

$$\sigma_N = \frac{3(L_2 - L_1)}{2b \cdot h^2} \cdot F \qquad (3)$$

where L_1 & L_2 are the inner & outer bridge spans, and b & h are the beam width and thickness (see Fig. 2).

The force range is shifted to higher values, and the presence of a constant nominal stress gives us a large zone away from the loading points where we can place the sensing resistors. This is a considerable advantage, as loading points, joints, etc. often have poorly defined boundary conditions, and cause parasitic stresses. Additionally, besides changing the beam geometry, the force range can also be tailored by adjusting, for a given L_2, the value of L_1, theoretically allowing the measurement of quite large forces. Furthermore, changing L_2 while keeping L_2–L_1 constant allows tailoring of the deflection while keeping the nominal force constant. Finally, as there is no clamping, issues with limited joint strength are avoided.

These bridge sensors do have some issues, which need to be addressed:

- One must find a convenient way of fixing the bridge strongly, while avoiding parasitic bending moments and hyperstatic assembly. This may be done by mounting the sensors on pins with soft glue, but, ideally, one should use thin sheet metal flexible hinges, which can then be mounted with hard glue and provide a much more reliable and well-defined geometry. In this work, we took the former solution because it is much more easily implemented.
- While parasitic stresses are avoided in the sensing resistors, they can nevertheless alter the stiffness of the structure, especially if the pairs of pins are spaced very closely.
- Finally, assembly is not as convenient as for the cantilever sensor: SMD style mounting of the beam is difficult. However, as these sensors are relatively large, it may be advantageous to simply include the electronics on the beam.

3.2. Fabrication

Bridge sensing beams were fabricated by screen-printing polymer thick-film conductor (Epotecny E212 conductive glue) and resistor (ESL 12116, 1 MOhm) on either PCB (FR4) or 96% alumina substrates (Fig. 4). Both polymer layers were polymerised in an oven at 150°C for 2 hours. The plane strain (bending) elastic modulus of our FR4 was determined to be $E^*_{FR4} = 19$ GPa, and the longitudinal gauge factor of ESL 12116 was found to be ca. 13 (with some dispersion). For simplicity, we used a single side (half-bridge) configuration, where the two passive resistors lie in the unstressed zone (Fig. 4, left).

Both 5 mm and 10 mm wide beams were fabricated, and assembled with thick alumina load and support slabs, using glued steel pins to define the load and support points (L_1 and L_2). In order to avoid parasitic stresses, we used soft silicone glue (mixes of Dow Corning QS8401 and Sylgard).

Figure 4. Bridge sensors: layout (left), screen printed samples (center), and assembled prototypes (right).

3.3. Properties

The parameters of some fabricated sensors are given in Table 2, together with the calculated stress, calculated span S_{calc} (with gauge factor = 13), and the actually measured span S_{mes} at full load. While the samples listed here are all 10 mm wide, the 5 mm ones were found to be fully functional as well. Examples of the obtained load responses are given in Fig. 5, for both 20 N sensors. The measured responses are linear, without significant hysterisis, and agree roughly with the calculated one, given the fact that the properties of the ESL 12116 resistor exhibit some dispersion: the FR4 sensors are roughly 10x more sensitive than the alumina ones. This must be weighed against the fact that alumina beams are compatible with standard high-temperature thick film processing and are hence potentially much more stable: the choice will depend on the application. We were able to achieve 100 N nominal force with relatively small thicknesses (0.80 mm). By using 1.27 mm thick alumina or FR4 substrates, we can roughly double this value, allowing measurement up to ca. 200 N with this principle, or even higher with thick FR4 laminates.

	Material (F=FR4; A=alumina)	F	F	F	F	A	A	A	
F	Force range	100	40	20	10	20	10	4	N
E^{*}	Elastic modulus	19	19	19	19	330	330	330	GPa
h	Beam thickness	0.80	0.80	0.80	0.50	0.50	0.25	0.25	mm
b	Beam width	10	10	10	10	10	10	10	mm
L_1	Inner span	11	4	4	4	7	10	4	mm
L_2	Outer span	15	15	15	15	15	15	15	mm
σ_N	Calculated nominal stress (3)	94	103	52	66	96	120	106	MPa
S_{calc}	Calculated span	32.1	35.3	17.6	22.6	1.9	2.4	2.1	mV/V
S_{mes}	Measured span	27.1	32.9	15.7	18.5	2.9	2.8	3.0	mV/V

Table 2. Parameters of "bridge" geometry sensors, and calculated & measured properties.

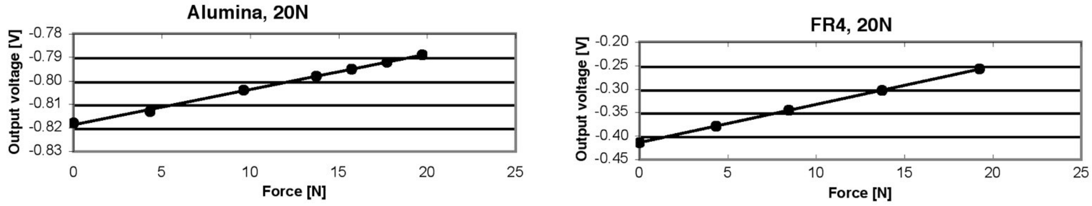

Figure 5. Raw (unamplified) response under load of 20 N FR4 and alumina sensors (10 V supply voltage).

4. CONCLUSIONS

In this work, we have seen that the force range of small soldered alumina cantilever thick-film piezoresistive force sensors is limited to ca. 100 mN at low ranges, mainly due to problems with very thin alumina substrates, and to ca. 2 N at high ranges, due to stresses in the solder joint. The range of cantilever sensors can be expanded, by using structured LTCC sensors at low forces [7], and probably by changing to glue joints at high forces, which give less severe stress concentrations. In this case, a limit of ca. 10 N is set by the available thick alumina substrates.

Further increasing the force necessitates a changeover to a "bridge" geometry, where the beam is under 4-point bending. Our preliminary prototypes have shown very promising results: despite the relatively crude assembly procedures, forces up to 100 N could be easily measured, and even higher values are possible by using available thicker substrates.

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